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A STUDY OF FATIGUE CRACKS IN CAR AXLES

PART II

A REPORT OF AN INVESTIGATION

CONDUCTED BY

THE ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS

IN COÖPERATION WITH

THE UTILITIES RESEARCH COMMISSION

BY

HERBERT F. MOORE
STUART W. LYON

AND

NORVILLE J. ALLEMAN

BULLETIN No. 197
ENGINEERING EXPERIMENT STATION

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UNIVERSITY OF ILLINOIS
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A STUDY OF FATIGUE CRACKS IN CAR AXLES

PART II

I. Introduction

1. *Introductory.*—In 1924 the Utilities Research Commission entered into coöperative relation with the University of Illinois for the study of fatigue failures of car axles under repeated stress. One bulletin* has already been published concerning the work of this investigation. The present bulletin deals especially with the practical question whether it is safe to use axles in which small fatigue cracks have started, if these axles are turned down below the bottom of the fatigue cracks and then put into service for which a smaller sized axle of sound steel would be safe. In other words, does the damaging effect of a fatigue crack injure the steel below the bottom of the crack, and if so to how great a depth?

2. *Acknowledgments.*—This study has been supported by funds contributed by the Utilities Research Commission, Wm. L. Abbott, Chairman. An Advisory Committee was appointed for this study as follows:

- H. A. Johnson, (Chairman), General Manager, Chicago Rapid Transit Company
- A. J. Authenrieth, Vice-President, Ice Dept., Middle West Utilities Company
- A. H. Daus, Supt. of Shops & Equipment, Chicago Rapid Transit Company
- D. W. Roper, Supt., Street Dept., Commonwealth Edison Company
- George E. Tebbetts, Supt. of Structures, Chicago North Shore & Milwaukee R. R. Company
- R. N. Wade, Supt. of Maintenance of Way, Chicago Rapid Transit Company

This committee has acted as an advisory committee for all the work reported in this bulletin, and several meetings of the committee have been held to consider the progress of the work. The tests described in this bulletin have been carried on in the Fatigue of Metals Laboratory at the University of Illinois, and the whole study has been closely allied with the Investigation of the Fatigue of Metals.†

*"A Study of Fatigue Cracks in Car Axles," Univ. of Ill. Eng. Exp. Sta. Bul. 165, 1927.
†For reports of the general investigation of the fatigue of metals, see Bulletins 124, 136, 142, 152, 156, 164, 165, 176, and 183 of the Engineering Experiment Station, University of Illinois.

The investigation has been carried on as a part of the work of the Engineering Experiment Station at the University of Illinois and has been under the general administrative direction of DEAN M. S. KETCHUM, director of the Engineering Experiment Station, and of Professor M. L. ENGER, head of the Department of Theoretical and Applied Mechanics.

3. *Summary of Previous Work with Car Axle Steel.*—The previous work in the study of the fatigue failure of car axle steel is reported in some detail in Bulletin 165, "A Study of Fatigue Cracks in Car Axles." A very brief summary of the conclusions reached follows:

By means of simple methods available for railroad shops, fatigue cracks in car axle steel were detected before complete failure of the specimen occurred. If the specimen was subjected to a stress but little above its endurance limit, the crack could be detected before one-half the "life" of the specimen under repeated stress had passed. If the axle was subjected to a very high stress repeated many times, the crack was not detected until failure was imminent.

From the results of tests on two sizes of specimens, it appeared that the size of the smallest crack which could be detected is about the same for small specimens as for large specimens. Hence when the crack is first detectable in a small specimen a larger proportion of the metal has been damaged than is the case when the crack is first detectable in a large specimen. For a small specimen, then, there will remain a shorter proportion of the "life" between the detection of a crack and final failure than is the case for a larger specimen. This indicates that the chances of detecting a fatigue crack before failure is imminent is better for full-size axles than for small specimens.

Test specimens in which a fatigue crack had been detected, and had spread to a definite length, showed a continuing spread of such a crack to failure, under subsequent cycles of stress having a magnitude of 64 per cent of the endurance limit of the virgin steel; but such a crack in a test specimen did not spread further under cycles of stress having a magnitude of 50 per cent of the endurance limit of the virgin steel.

For the axles tested the range of strength values of the steel was found to be as follows (in pounds per square inch):

Proportional Elastic Limit, from 40 800 to 53 500

Ultimate Tensile Strength, from 91 700 to 105 100

Endurance Limit for an indefinitely large reversal of Flexural Stress (Tests of small "Farmer" specimens) about 35 000

4. *Scope of Bulletin.*—The particular phase of car axle problem with which this bulletin deals is the problem concerning the safety of the practice of turning down car axles in which a fatigue crack has developed, and then using them for smaller axles or shafts. This bulletin records fatigue tests on car axle steel as received, and on speci-

mens of car axle steel which, after a fatigue crack had developed, were turned down slightly below the root of the crack, and their fatigue strength then compared with that of the virgin steel. Axles of several different kinds of steel furnished specimens for these tests, and testing machines permitting the use of two different sizes of specimens were used.*

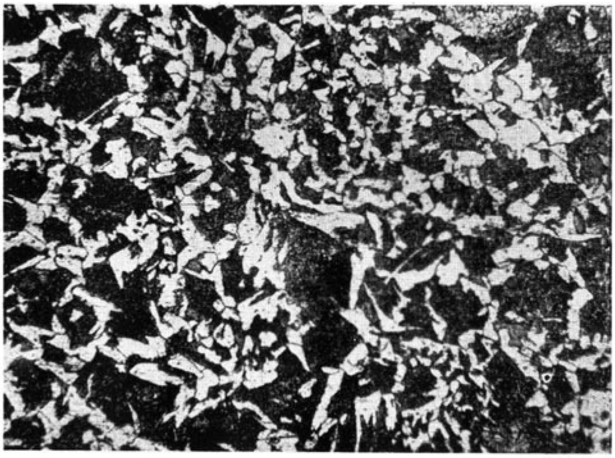
II. Test Data and Results

5. *Materials, Test Specimens, and Testing Apparatus.*—A number of axles furnished the material for this study. All were furnished by the Chicago Rapid Transit Company. All had been in service, and the service of each axle is shown in Table 1.

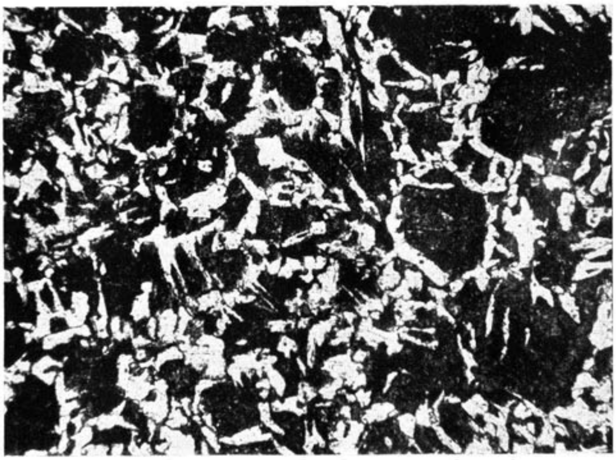
The chemical analyses for the various axles, given in Table 2, are analyses made either by the Robt. W. Hunt Laboratory or by the Chemical Laboratory at the University of Illinois. Tensile tests were made on specimens of each axle and the results of these tests are given in Table 3. All of the axles from which specimens were cut were heat-treated, except axles 1141 and 1144. Table 4 gives the status of the heat treatment of the axles tested. In general, the exact heat treatment is not known, but the specifications under which the axles were purchased called for a heat treatment consisting of an oil quench and subsequent draw to be carried out on the axle after forging.

Figures 1 to 6 inclusive show micrographs of the steel in various axles studied. Micrographs of both longitudinal and transverse sections are shown. A comparison of the micrographs of axles 1141 and 1144, which were not heat-treated, with those of the other axles, all of which were heat-treated, shows plainly the effect of heat treatment on the grain structure of the steel. The structure of the steel of axles 1141 and 1144 is of the Widmanstätten type in which the ferrite and the pearlite is distributed in a coarse "dendritic"† grain structure along what are apparently planes of cleavage, along which the strength of the steel is probably low. In the heat-treated steels, this Widmanstätten structure is fairly well broken up, although the micrographs indicate that still further improvement in grain structure might be effected. However, there is distinct evidence that on a piece of steel of the size of a car axle, heat treatment does have an effect plainly appreciable well in toward the center of the axle.

*Tests of small standard "Farmer" fatigue specimens (Fig. 10a and 10b) were also made.
†A dendrite is a branching figure resembling a shrub or a tree.



Longitudinal Section

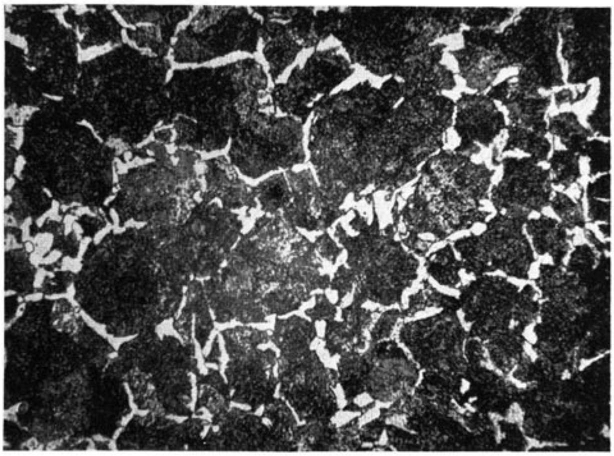


Transverse Section

FIG. 1. MICROGRAPHS OF AXLE 1680, HEAT 25092
(x 100)

Etched with 2 per cent nitric acid in alcohol.

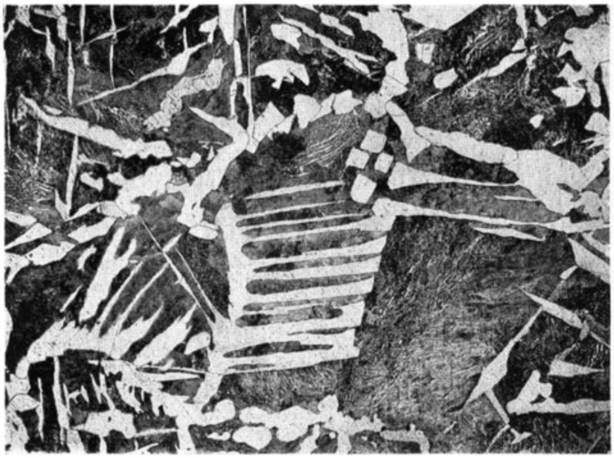
Longitudinal Section



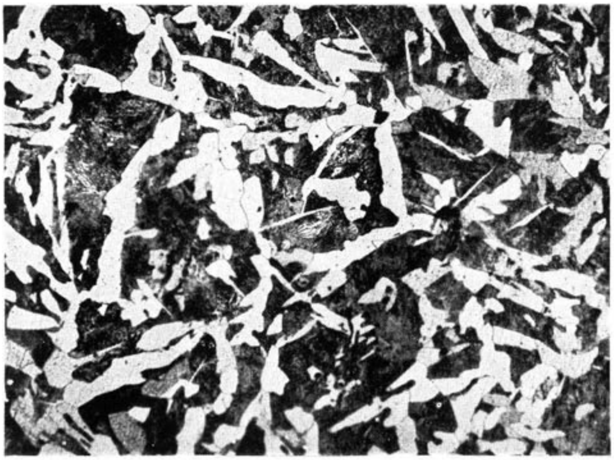
Transverse Section

FIG. 2. MICROGRAPHS OF AXLE 1840, HEAT 28120
(x 100)

Etched with 2 per cent nitric acid in alcohol.



Longitudinal Section

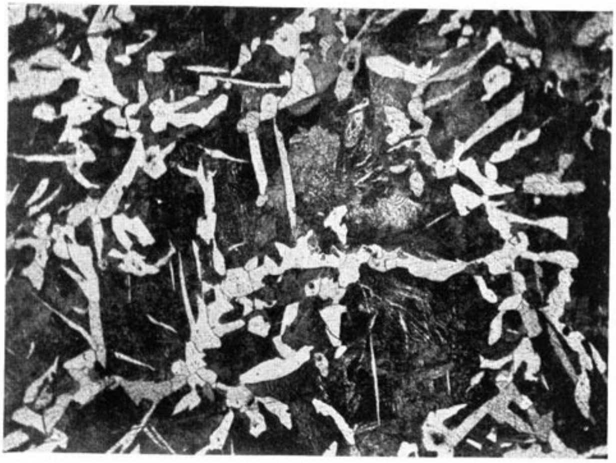


Transverse Section

FIG. 3. MICROGRAPHS OF AXLE 1141
(x 100)

Etched with 2 per cent nitric acid in alcohol.

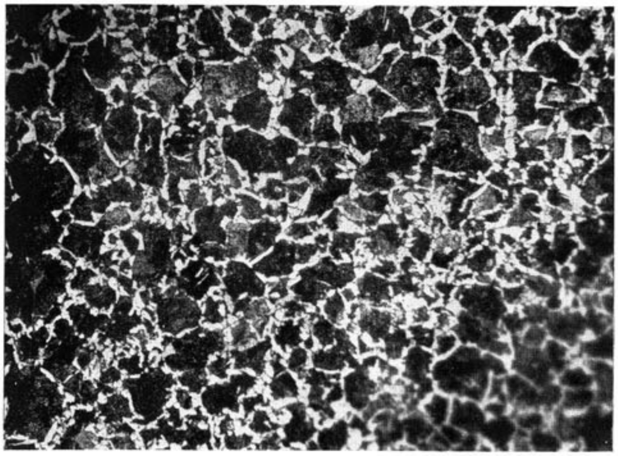
Longitudinal Section



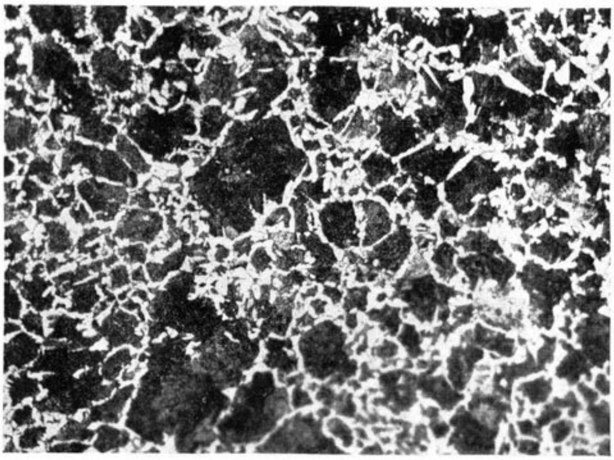
Transverse Section

FIG. 4. MICROGRAPHS OF AXLE 1144
(x 100)

Etched with 2 per cent nitric acid in alcohol.



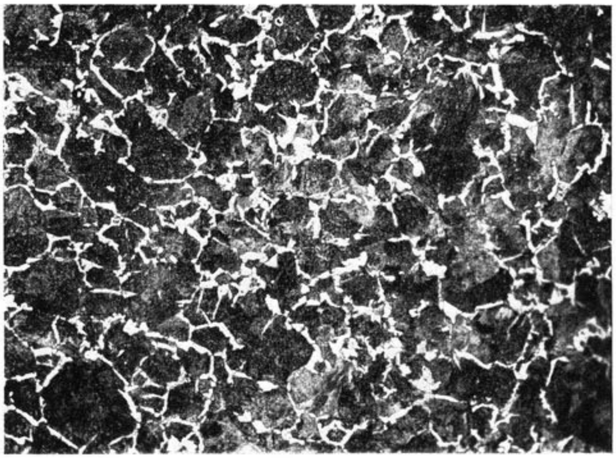
Longitudinal Section



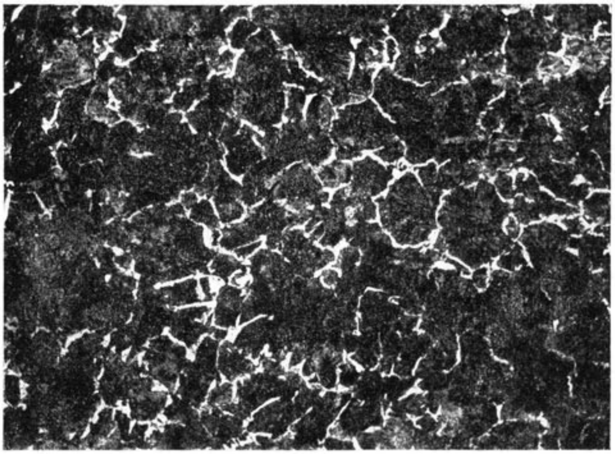
Transverse Section

FIG. 5. MICROGRAPHS OF AXLE 1618, HEAT 28115
(x 100)

Etched with 2 per cent nitric acid in alcohol.



Longitudinal Section



Transverse Section

FIG. 6. MICROGRAPHS OF AXLE 61, HEAT 9387
(x 100)

Etched with 2 per cent nitric acid in alcohol.

TABLE 1

SERVICE HISTORY OF AXLES TESTED

All axles were solid, without central counterbore

Designation	Maximum Diameter in.	History
Axle 1680, Heat 25092.....	6	Placed in service Feb. 4 1916; has run 371 160 miles
Axle 1840, Heat 28120.....	6	Placed in service May 19, 1916; has run 357 329 miles
Axle 1141, Heat ———.....	4¾	Placed in service September, 1908; has run approximately 600 000 miles
Axle 1144, Heat ———.....	4¾	Placed in service September, 1908; has run approximately 600 000 miles
Axle 1618 "A", Heat 28115.	6	Taken out of service after having run 337 238 miles
Axle 61 "B", Heat 9387....	6	Taken out of service after having run 186 056 miles

TABLE 2

CHEMICAL COMPOSITION OF AXLES TESTED

Chemical content is given in per cent

Axle No.	Heat No.	Carbon	Manganese	Silicon	Phosphorus	Sulphur
1680................	25 092	0.45	0.49	0.15	0.019	0.046
1840................	28 120	0.47	0.66	0.17	0.015	0.035
1141*...............	......	0.537	0.69	0.035	0.034	0.042
1144*...............	......	0.534	0.38	0.028	0.042	0.041
1618"A"............	28 115	0.50	0.49	0.165	0.018	0.046
61"B"...............	9 387	0.55	0.48	0.22	0.008	0.030

*No record of heat number.

TABLE 3

PHYSICAL PROPERTIES OF STEEL IN AXLES

Axle No.	Propt'l. Elastic Limit	Yield Point	Ultimate Tensile Strength	Elongation in two inches	Reduction of Area	Charpy Impact Energy of Rupture ft. lb.
	lb. per sq. in.			per cent		
1680..............	41 700	42 500	81 400	29.0	54.7	11.6
1840..............	47 300	51 000	96 700	25.2	47.4	5.2
1141..............	24 600	30 000	76 600	39.1	26.1	3.67
1144..............	30 700	33 800	84 100	30.7	19.5	6.52
1618"A"..........	44 800	45 600	87 800	49.3	27.2	18.55
61"B"............	45 700	48 000	94 600	43.7	28.2	12.40

TABLE 3 (*Continued*)
PHYSICAL PROPERTIES OF STEEL IN AXLES

Axle No.	Brinell Hardness Number	Sclero-scope Hard. No.	Rockwell Hardness Numbers		Endurance Limit of 1-in. or 2-in. Specimens*	Endurance Limit of Farmer Specimens†
			"B"	"C"	lb. per sq. in.	
1680	151.2	25.4	82.9	0.0	......	27 000
1840	176.9	27.1	90.4	10.0	......	29 000
1141	134.2	27.1	78.5	−5.0	20 000	29 000
1144	149.0	27.5	82.5	1.0	23 000	32 000
1618"A"	156.4	26.0	86.0	4.0	26 000	36 000
61"B"	174.0	29.0	90.0	10.0	27 000	37 000

*See Fig. 8 and Fig. 9.
†See Fig. 10.

TABLE 4
HEAT TREATMENT OF AXLES

Axle No.	Heat No.	Heat Treatment
1680	25 092	Oil quench and draw*
1840	28 120	Oil quench and draw*
1141	......†	Used as forged
1144	......†	Used as forged
1618 "A"	28 115	Oil quench and draw*
61 "B"	9 387	Oil quench and draw*

*Exact heat treatment not recorded; specifications called for an oil quench and subsequent draw to be carried out on the axle after forging.
†No record of heat number.

The test specimens for the fatigue tests were cut from various parts of the axle. Figure 7 shows the locations of fatigue specimens in the axles. The first series of tests made several years ago used specimens like those shown in Fig. 8. Later tests used specimens like those shown in Fig. 9a with a maximum diameter at critical section of 2 inches. It is to be noted that there is some stress concentration at the fillets of these specimens. The fillets were made with the same radius for full-size test specimens and for specimens turned down below cracks, hence this stress concentration factor is assumed to remain constant.*

*Stress-concentration factor is the ratio of actual stress at fillets, holes, grooves, or other sudden changes of size or shape of cross-section to the nominal stress as computed by the ordinary formulas of Mechanics of Materials, which take no account of such sudden changes. Stress-concentration at axle fillets is discussed in Bulletin 165, p. 9 and p. 13.

TABLE 5
TEST DATA OF FATIGUE TESTS

Specimen No.	Stress in lb. per sq. in.	Cycles for Failure
Tests of small ("Farmer") specimens cut from axle; see Fig. 10a		
Axle 1141		
1141-7-14-1.....	50 000	18 300
1141-7-14-7.....	37 000	492 300
1141-7-14-4.....	34 000	628 900
1141-7-14-6.....	30 000	3 130 300
1141-7-14-8.....	30 000	11 080 400
1141-7-14-6A....	29 000	103 519 400*
Axle 1144		
1144-12-18-8....	52 000	43 100
1144-12-18-7....	49 000 R	54 100
1144-12-18-1....	45 000	178 600
1144-12-18-2....	42 000 R	949 700
1144-12-18-5....	40 000	507 400
1144-12-18-2A...	35 000	2 634 500
1144-12-18-3....	34 000	3 608 700
1144-12-18-4....	33 000	15 014 000
1144-12-18-2....	32 000	401 699 400*
1144-12-18-7....	31 000	99 594 100*
Tests of small ("short Farmer") specimens cut from axle; see Fig. 10b		
Axle 1618 Heat 28115		
A-4-7-4.........	50 000	50 200
A-4-7-6.........	47 000 R	328 500
A-4-7-1.........	45 000	1 703 200
A-4-7-5.........	40 000	1 992 800
A-4-7-3.........	39 000	1 919 800
A-4-7-2.........	38 000	1 643 500
A-4-7-6.........	35 800	49 574 500*
Axle 61 Heat 9387		
B-1-1..........	55 000	8 200
B-1-6..........	50 000 R	35 100
B-1-3..........	48 000 R	233 700
B-1-4..........	42 000	3 378 100
B-1-5..........	40 000	2 016 200
B-1-2..........	38 000	850 500
B-1-6..........	37 000	27 977 000*
B-1-3..........	35 000	10 182 600*
Tests of small ("Farmer") specimens cut from axle		
Axle 1680 Heat 25092		
3-1680-2......	45 000	162 000
3-1680-3......	40 000	473 600
3-1680-4......	38 000	1 490 700
3-1680-5......	37 000	7 827 100
3-1680-1......	35 000	5 201 200
3-1680-6......	34 000	94 142 600*
3-1680-0......	33 000	104 974 900*
Axle 1840 Heat 28120		
1-1840-7......	60 000 R	3 100
1-1840-1......	55 000 R	92 900
1-1840-5......	52 000 R	144 000
1-1840-4......	50 000	266 800
1-1840-8......	45 000	343 600
1-1840-3......	43 000	1 558 600
1-1840-2......	42 000	880 200
1-1840-5......	41 000	13 581 900*
1-1840-7......	40 000	20 638 500*
1-1840-1......	38 000	19 116 500*
No crack in specimen previous to testing; 1-inch specimens. See Fig. 8		
Axle 1141		
1141-7-14-1...	34 000 R	111 800
1141-7-14-4...	25 000	816 200
1141-7-14-3...	23 000	1 468 600
1141-7-14-2...	21 500	2 567 500
1141-7-14-1...	20 000	15 206 400*
Axle 1144		
1144-12-18-3..	38 000 R	100 900
1144-12-18-4..	35 000	135 000
1144-12-18-2..	29 000	669 200
1144-12-18-1..	25 000	2 132 500
1144-12-18-3..	23 000	30 952 600*
No crack in specimen previous to testing; 1-inch specimens. See Fig. 8		
Axle 1680 Heat 25092		
AL..........	32 000	578 300
BL..........	30 000 R	452 800
AL..........	28 200	1 085 000
BL..........	27 000	3 981 000*
CL..........	26 100	3 049 500*

*Did not fail.
R—Retest.

TABLE 5 (*Concluded*)

TEST DATA OF FATIGUE TESTS

Specimen No.	Stress in lb. per sq. in.	Cycles for Failure
Axle 1840 Heat 28120		
S	35 000 R	135 100
BS	33 100 R	200 400
SS	31 000	537 100
S	31 000	1 139 900*
DL	30 700 R	630 000
AS	30 000	690 200
AL	29 700	443 500
BS	29 500	2 242 100*
GL	29 000	11 411 800*
FL	29 000 R	800 000
EL	29 000	472 600
DL	27 900	3 759 100*
FL	25 000	3 536 200*
No crack in specimen previous to testing; 2-inch specimens. See Fig. 9		
Axle 1618 Heat 28115		
A-1-1	39 000	53 000
A-2-2	35 000 R	248 800
A-3-4	34 000	207 000
A-4-6	30 000	712 000
A-4-7	28 000	1 015 000
A-2-2	26 000	10 767 300*
Axle 61 Heat 9387		
B-1	39 300	89 500
B-2	33 000	393 200
B-1	33 000 R	923 300
B-3	28 000	2 043 000
B-4	27 000 R*	15 562 300*
B-4	24 000	20 519 900*
Standard crack developed, then specimen turned down to base of crack; 1-inch specimen. See Fig. 8		
Axle 1680 Heat 25092		
CS	23 000	1 034 200
Axle 1840 Heat 28120		
GL	28 500 R	708 800*
AS	28 000	320 000
GL	28 000 R	13 169 700*
GL	25 000 R	15 381 100*
BS	23 300 R	1 732 700
GL	22 000	28 137 700*
BS	20 000	10 040 200*

Specimen No.	Stress in lb. per sq. in.	Cycles for Failure
Standard crack developed in specimen, then specimen turned down 1/16 inch below bottom of crack; 1-inch specimen. See Fig. 8		
Axle 1141		
1141-7-14-1	20 000	11 669 500*
1141-7-14-2	20 000	22 438 600*
1141-7-14-3	20 000	29 559 400*
1141-7-14-4	22 000	559 600
Axle 1144		
1144-12-18-1	21 000	21 325 200*
1144-12-18-2	23 000	17 791 800*
1144-12-18-3	22 000	15 842 800*
1144-12-18-4	21 000	1 966 700*
Standard crack developed in specimen, then specimen turned down 1/16 inch below bottom of crack; 1-inch specimen. See Fig. 8		
Axle 1680 Heat 25092		
EL	27 000	7 069 900
Axle 1840 Heat 28120		
GL	40 000 R	302 600
GL	35 000 R	18 878 700*
FL	33 000 R	411 200
GL	29 000	11 411 800*
FL	28 000	13 605 700*
Standard crack developed in specimen, then specimen turned down 1/16 inch below bottom of crack; 2-inch specimen. See Fig. 9		
Axle 1618 Heat 28115		
A-4-7	27 000	9 660 500
A-4-6	26 000	17 826 900*
A-1-1	25 000	11 476 500*
A-2-2	25 000	15 365 500*
Axle 61 Heat 28115		
B-4	33 000R	923 300
B-3	28 000	4 668 200*
B-1	27 000	15 044 200*
B-2	26 000	20 163 500*

*Did not fail. R—Retest.

R*—This specimen first ran at 24 000 lb. per sq. in. for 20 519 900 cycles without showing any crack. It was turned down and after a year's seasoning it was again used to determine endurance limit. As no crack appeared in the first run, the surface material which was subjected to understressing was removed. This specimen is considered as virgin material in determining the endurance limit.

TABLE 6
RESULTS OF FATIGUE TESTS OF SPECIMENS CUT FROM CAR AXLES

Axle	Heat	Endurance Limit—lb. per sq. in.				
		Virgin Metal			Metal at base of crack	Metal 1/16 in. below base of crack
		"Farmer" specimens*	1-inch specimens†	2-inch specimens‡		
1141	......¶	29 000	20 000	......	....	Not less than 20 000
1144	......¶	32 000	23 000	......	....	Not less than 23 000
1618"A"	28 115	36 000	......	26 000	....	Not less than 26 000
61"B"	9 387	37 000	......	27 000	....	Not less than 27 000
1680	25 092	35 000	27 000	......	Not more than 23 000	Approximately 27 000
1840	28 120	41 000	29 000	......	Not more than 23 000	Approximately 32 000

*See Fig. 10a or Fig. 10b.
†See Fig. 8.
‡See Fig. 9.
¶No record of heat number.

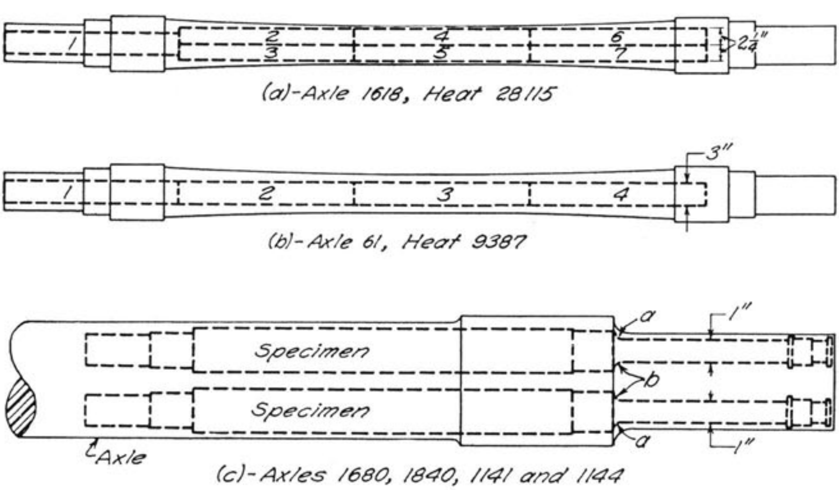


FIG. 7. LOCATION OF FATIGUE SPECIMENS IN AXLES

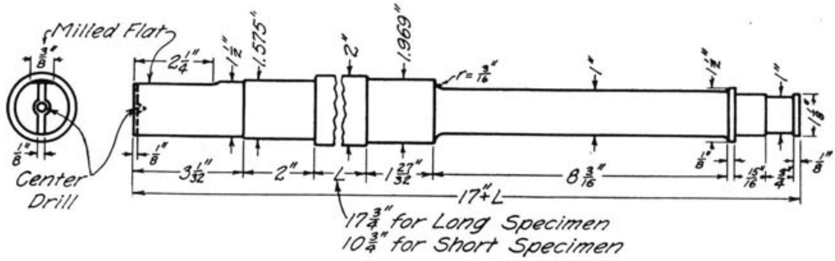


FIG. 8. 1-INCH FATIGUE SPECIMEN

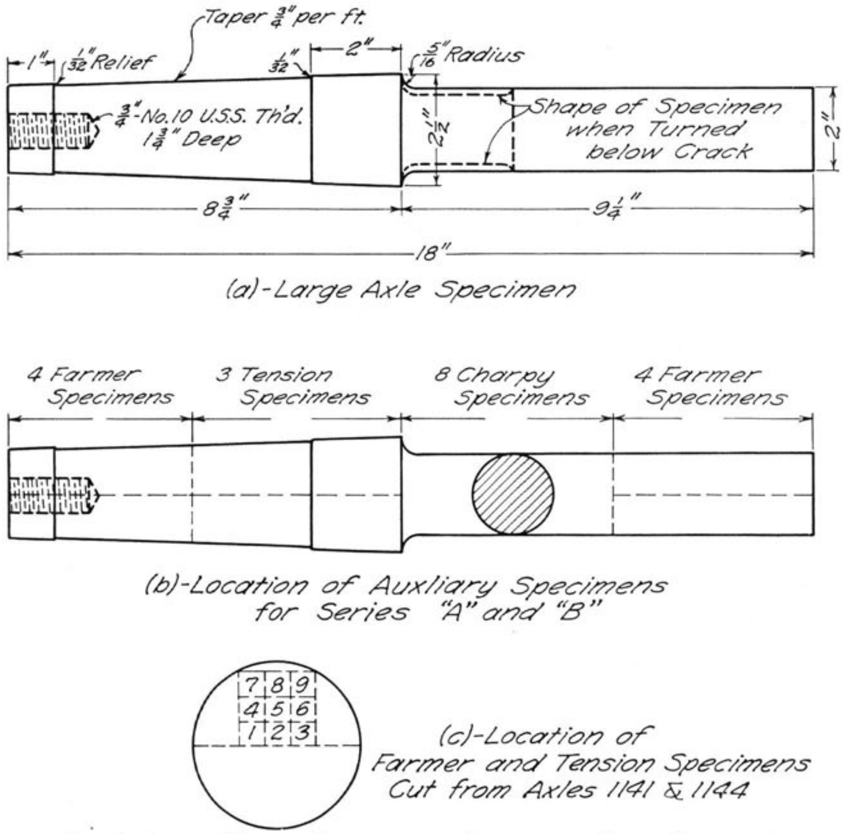


FIG. 9. 2-INCH FATIGUE SPECIMEN AND LOCATION OF SMALL SPECIMENS CUT FROM IT

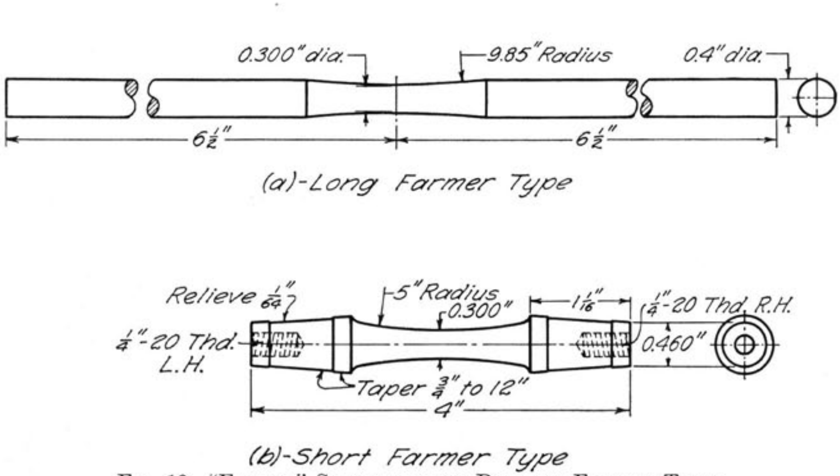


FIG. 10. "FARMER" SPECIMENS FOR ROUTINE FATIGUE TESTS

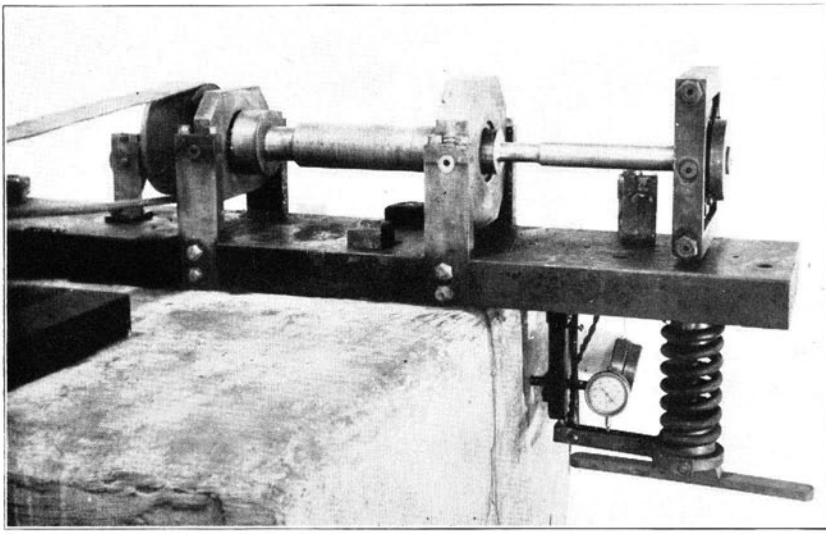


FIG. 11. FATIGUE TESTING MACHINE FOR 1-INCH SPECIMENS

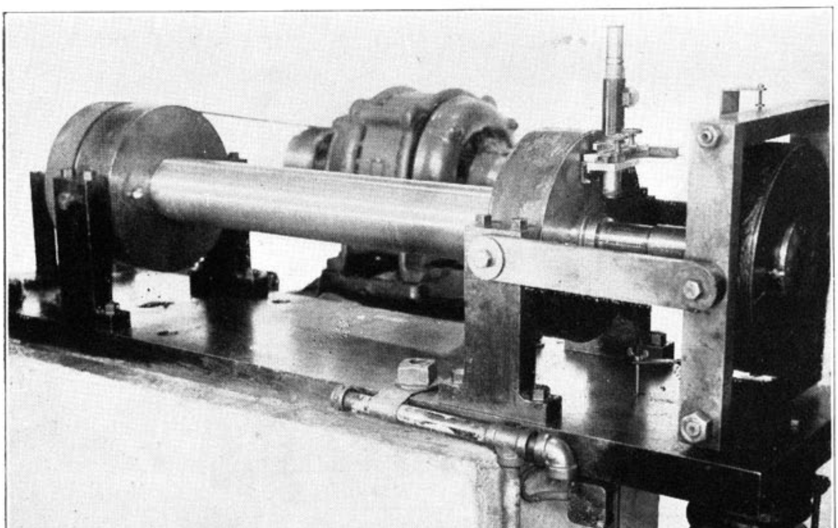


FIG. 12. FATIGUE TESTING MACHINE FOR 2-INCH SPECIMENS

Note microscope for examining specimen for cracks.

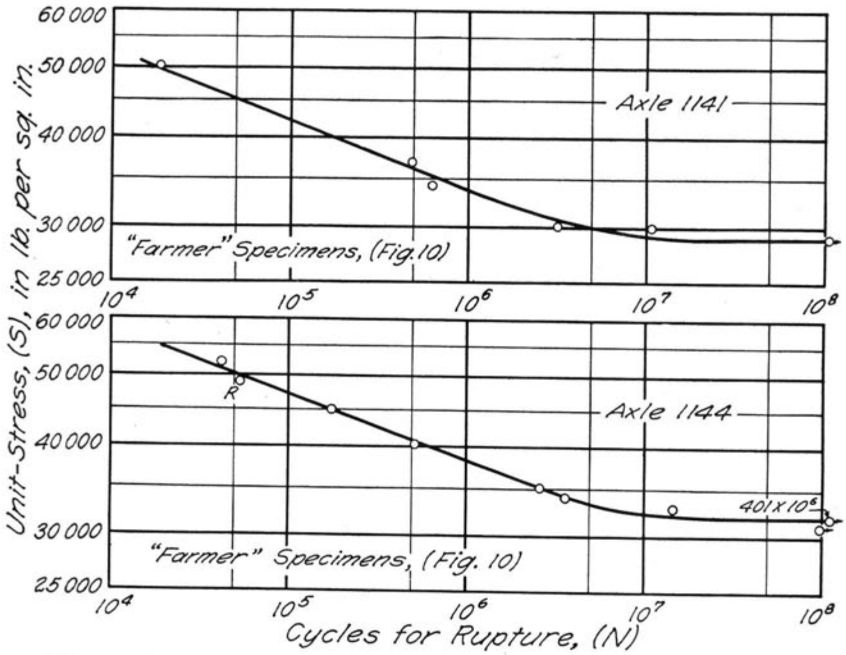


FIG. 13. S-N DIAGRAMS FOR SMALL SPECIMENS FROM AXLES 1141 AND 1144

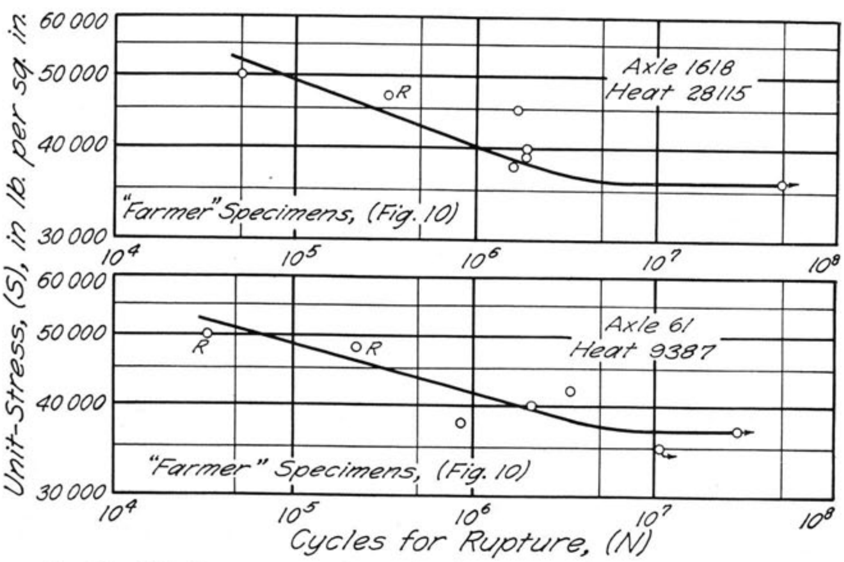


FIG. 14. S-N DIAGRAMS FOR SMALL SPECIMENS FROM AXLES 1618 AND 61

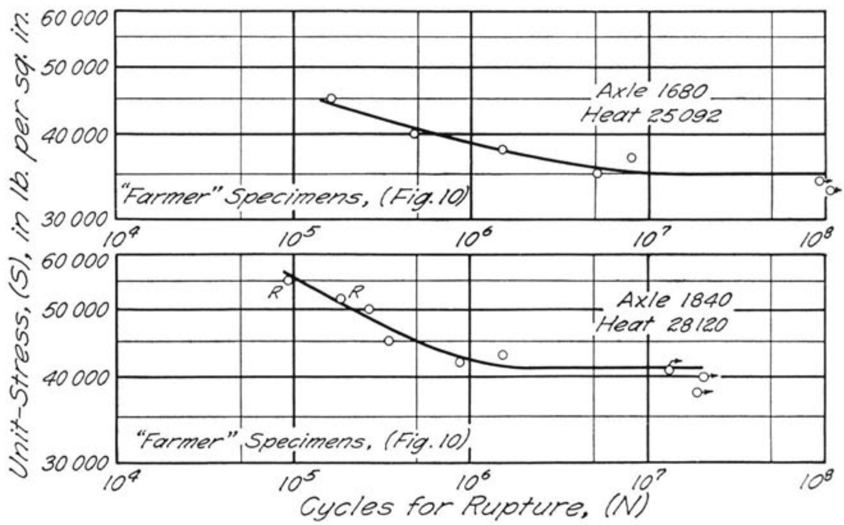


FIG. 15. *S-N* DIAGRAMS FOR SMALL SPECIMENS FROM AXLES 1680 AND 1840

Figure 9 shows the locations, in a 2-inch specimen, from which various test specimens were cut for determining the mechanical properties of the steel. For determining the endurance limit of the metal in the axles, fatigue specimens of the form and size shown in Fig. 10a and 10b were used. These are the fatigue specimens used in the routine work of the Fatigue of Metals laboratory, and are known as "Farmer" specimens.

The testing machine used for the 1-inch specimens is shown in Fig. 11. The specimen itself is the shaft of the machine, and the overhanging end of the specimen is a rotating-cantilever beam, in which the bending stress is completely reversed for each revolution of the specimen. The rear bearing of the machine can be moved backward to accommodate the longer specimen shown in Fig. 8. In this machine the bending load on the specimen is applied by a calibrated spring and the compression of the spring, and hence the load on the specimen is measured by means of a dial gage micrometer.

Figure 12 is from a photograph of the testing machine used for the 2-inch specimens. Like the machine shown in Fig. 11, this is a rotating-cantilever type of machine. The tapered end of the specimen (see Fig. 9a) fits into a socket in the hollow main shaft of the machine. The load is applied through a calibrated spring and the compression of this spring is measured directly on a steel scale.

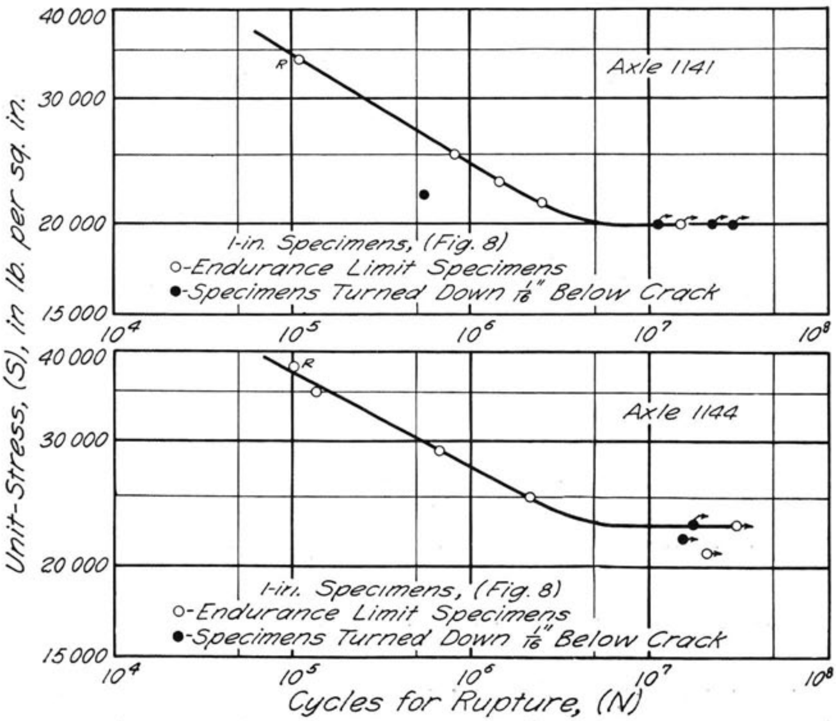


FIG. 16. *S-N* DIAGRAMS FOR 1-INCH SPECIMENS FROM AXLES 1141 AND 1144

6. *Procedure in Tests of Specimens Turned Down Below Cracks.*—The procedure in the experimental study of steel just below the bottom of fatigue cracks was as follows: Fatigue cracks of a given length were produced in specimens by applying cycles of stress above the endurance limit and making frequent examinations with a microscope magnifying ten diameters (see Fig. 12) to detect when the crack had grown to a certain arbitrary length (about 0.1 inch). The portion of the length of specimen under high stress (near the fillet) was polished by using successively No. 1, No. 0, No. 00, and No. 000 emery polishing paper. The polishing was circumferential in direction. The depth of each crack was estimated from its length, by assuming the depth to equal the distance from the chord to the arc of a circle.* Each specimen was then turned down to a diameter equal to that at the bottom of the estimated crack, and a careful examination made both by the mechanician and by one of the laboratory staff to see if the

*One specimen with a "standard" crack in it was broken by static bending, and this assumption was found to be approximately true for that specimen.

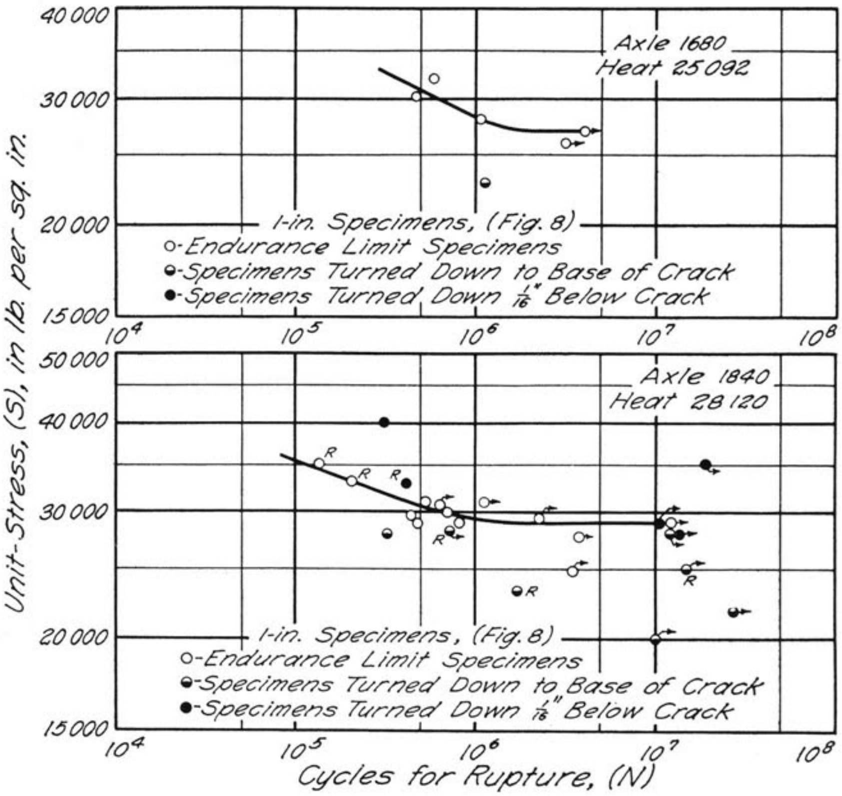


FIG. 17. *S-N* DIAGRAMS FOR 1-INCH SPECIMENS FROM AXLES 1680 AND 1840

crack had been removed. This examination was made with a low-power microscope with a magnification of 10 diameters, which was attached to a support on the carriage of the lathe. If traces of the crack were still visible more metal was removed. When no traces of a crack could be seen the specimen was polished and subjected to a repeated-stress test.

Another series of specimens was tested in which, after the specimen had been turned down to the apparent bottom of the crack, a further one-sixteenth of an inch of metal was removed (diameter of specimen reduced 1/8 inch). Then the specimens were polished and subjected to cycles of reversed bending at a stress equal to or very slightly above the endurance limit for uncracked specimens from the same axle.

The data of all fatigue tests of turned-down specimens are given in Table 5; Figs. 13 to 18 inclusive are stress-cycle (or *S-N*) diagrams, showing the data graphically.

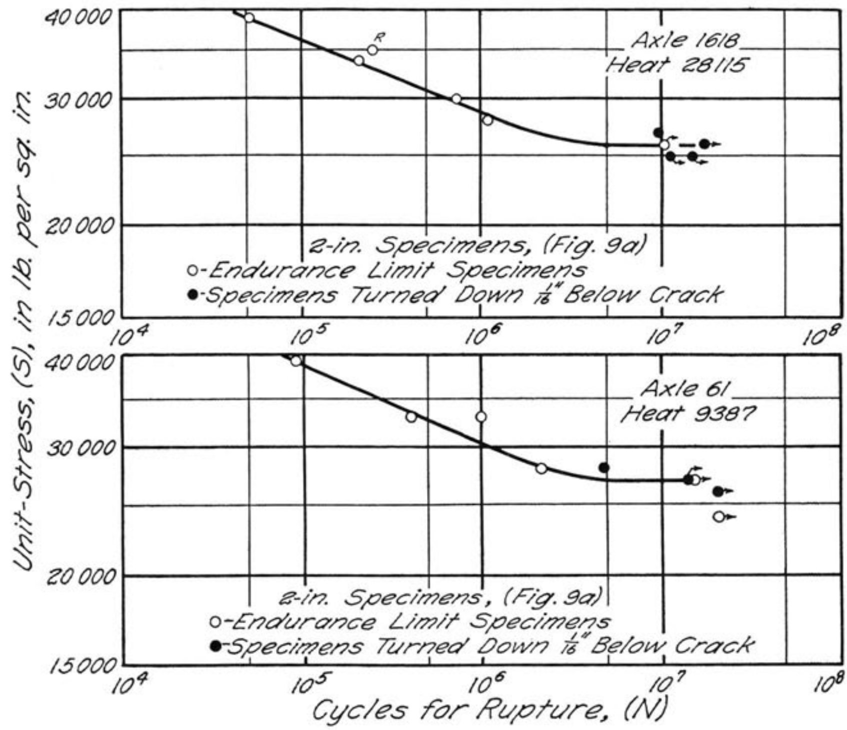


FIG. 18. *S-N* DIAGRAMS FOR 2-INCH SPECIMENS FROM AXLES 1618 AND 61

7. *Results of Tests of Specimens Turned Down Below Cracks.*—Table 6 gives the results of the fatigue tests on such specimens as were turned down just to the apparent bottom of the fatigue cracks, and on specimens turned down $\frac{1}{16}$ of an inch below the bottom of fatigue cracks. The specimens tested after being turned down just to the bottom of the fatigue crack, show a distinct reduction of fatigue strength below that of the virgin metal. The most marked case of this is found for the specimens from axle 1840 from heat 28120. The endurance limit in this case was reduced from 29 000 lb. per sq. in. to about 23 000, or 21 per cent below that of the virgin metal.

For the specimens turned down $\frac{1}{16}$ of an inch below the apparent bottom of the crack, the results of all the fatigue tests, both on the 1-inch specimens and on the 2-inch specimens, show no reduction of endurance limit below that of the virgin metal. In fact, in the case of axle 1840 a slight increase is observed. This increase may be due to the beneficial effect of repeated "under-stressing" of the steel.*

*See Bulletin 142, Engineering Experiment Station, University of Illinois, page 27.

8. *Conclusions.*—The following conclusions may be drawn:

(1) The results of these series of tests indicate that the practice of salvaging an axle in which a fatigue crack has developed by turning it down to a smaller size is safe, if the material is removed to the depth of at least $\frac{1}{16}$ of an inch below the apparent bottom of the fatigue crack.

(2) If the material is removed only to the apparent bottom of the fatigue crack, the evidence of these tests indicates that the damaged material is not all removed, and that the fatigue strength of an axle so treated may be materially less than would be expected from the fatigue strength of the virgin steel.

The conclusion as to the unimpaired fatigue strength of the steel $\frac{1}{16}$ inch below the bottom of a fatigue crack is based on tests of specimens from six different axles, and on tests of two sizes of specimens,—1 inch and 2 inches in diameter, respectively.

Although not directly related to the main problem of this investigation, it is of interest to note that the tests showed that the beneficial effects of heat treatment are appreciable well in toward the center of a solid piece of steel as large as a car axle (about $6\frac{1}{4}$ inches in diameter).

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